Review Article

Physiology and Radiology of the Normal Oral and Pharyngeal Phases of Swallowing

Wylie J. Dodds,[1] Edward T. Stewart,[1] and Jeri A. Logemann[2]

During the past decade, considerable interest has developed in the radiologic examination of the oral and pharyngeal phases of swallowing [1]. This interest has been stimulated by advances in swallowing therapy. In this report, we review (1) the normal physiology of swallowing, (2) methods for radiologic examination of the mouth and pharynx, and (3) the radiologic appearance of normal oral and pharyngeal swallowing. See pages 965–974 for a report on abnormalities of swallowing and therapeutic techniques designed to improve abnormal oral and pharyngeal swallowing functions.

Normal Physiology

Swallowing normally occurs as an orderly physiologic process that transports ingested material and saliva from the mouth to the stomach [2, 3]. This process usually occurs so smoothly and effortlessly that it belies the complexity of the neuromuscular apparatus that executes and orchestrates the swallowing sequence. Generally, swallowing is considered to be voluntary because deglutition can be elicited by cerebral input when one thinks "swallow." Many swallows, however, particularly those between meals, occur without conscious input. Spontaneous swallowing occurs at about 1/min in awake subjects [4]. This high swallowing rate is initiated by salivation, which occurs at about 0.5 ml/min and must either be swallowed or expectorated. The high basal rate of swallowing during wakefulness leads to about 1000 swallows daily or 3 to 4 million per decade. Although the majority of swallows occur subconsciously in response to salivation, some saliva swallows are voluntary, and close clustering of voluntary swallows is evoked consciously during eating. During eating, swallowing is associated with increased salivation, which facilitates the initiation of swallowing and acts as a lubricant. During sleep, salivation and swallows nearly cease [5], but the awake pattern recurs rapidly during arousals from sleep.

Phases of Swallowing

For descriptive purposes, swallowing is divided into four phases: (1) preparatory phase, (2) oral phase, (3) pharyngeal phase, and (4) esophageal phase. The preparatory phase involves mastication of a bolus and mixing it with saliva. The bolus is sized, shaped, and positioned on the tongue ready for swallowing. During the oral phase, the bolus is propelled from the oral cavity into the pharynx. The normal pharyngeal phase involves bolus transport from the oropharynx into the esophagus without aspiration. During the esophageal phase, not discussed further in this report, the bolus is propelled the length of the esophagus into the stomach.

Anatomy

The anatomic components of the head and neck swallowing apparatus include (1) bony and cartilaginous support structures, (2) striated muscles, and (3) neural elements. The bony

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[1] Department of Radiology, the Medical College of Wisconsin, Froedtert Memorial Lutheran Hospital, 9200 W. Wisconsin Ave., Milwaukee, WI 53226. Address reprint requests to W. J. Dodds.

[2] Department of Communication Sciences and Disorders, Neurology and Otolaryngology-Head and Neck Surgery, Northwestern University, Evanston, IL 60208.

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maxillary palatal arch apposes the tongue during the oral phase of swallowing. Another solid structure is the hinged mandible that allows chewing during the preparatory phase, but becomes fixed in a closed position during swallowing. The pharyngobasilar fascia originates from the basiocciput of the skull and anchors the pharynx to the skull base. The cervical spine provides a firm but flexible posterior support for the pharynx. Membranous planes that ensheathe the pharynx allow its free axial movement during swallowing. Suspended by the suprahyoid musculature, the hyoid bone serves as an intermediate supporting structure for the larynx and platform for the tongue (Fig. 1). The thyrohyoid membrane and thyrohyoid muscles connect the larynx to the hyoid. The larynx forms the anterior wall of the hypopharynx, and the posterior tongue forms the anterior wall of the oropharynx.

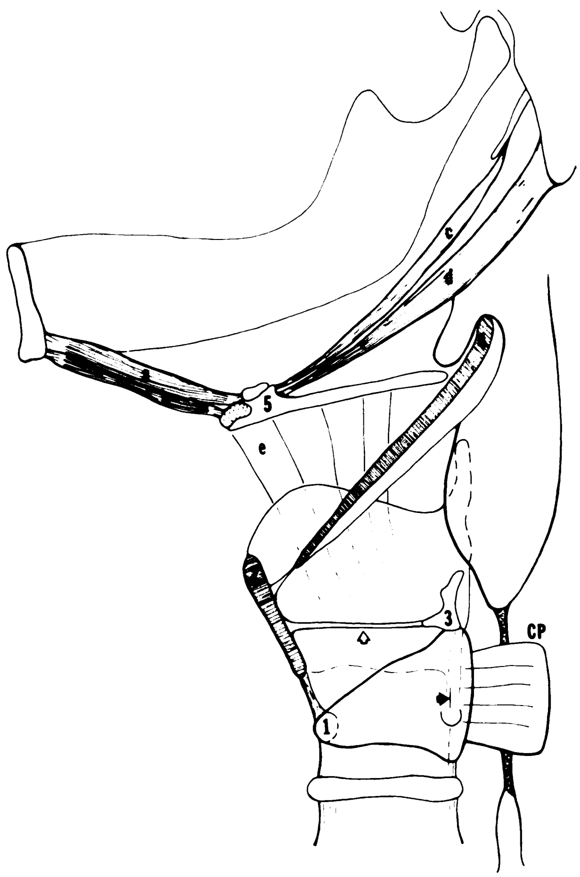


Fig. 1.—Schematic representation of suspension of hyoid and larynx. Hyoid (5) is suspended from mandible and skull by four suprahyoid muscles: anterior pair—geniohyoid (b) and anterior digastric (a); posterior pair—stylohyoid (c) and posterior digastric (d). These muscles generate a superior and anterior movement of hyoid during swallowing. Larynx is attached to hyoid by paired thyroglossus muscles (e) and thyrohyoid membrane (*not shown*). Larynx consists of following cartilages: epiglottic (4), thyroid (2), cricoid (1), and arytenoid (3). Epiglottis is attached anteriorly to thyroid cartilage, just superior to ventral attachment of vocal cords (*open arrow*) on thyroid cartilage. Posteriorly, vocal cords attach to vocal process of arytenoids. Arytenoids sit on superior margin of cricoid plate. Posterior border of trachea is indicated by *solid arrow*. Just below this arrow is a hinge joint between inferior cornu of thyroid cartilage and cricoid cartilage. Shortening of cricothyroid muscle (*not shown*) approximates anterior thyroid cartilage to anterior rim of cricoid cartilage. This movement passively tenses vocal cords and tucks introitus of laryngeal vestibule ventrally under free margin of epiglottis. During swallowing, larynx makes a supero-anterior excursion because of its attachments to hyoid. Thyrohyoid muscles (e) contract so that larynx approximates and becomes locked to hyoid. Thus, superior movement of larynx exceeds that of hyoid. Shortening of thyrohyoid muscles also rotates epiglottis into a horizontal position. Because of its attachment to cricoid, cricopharyngeus (CP) moves superiorly about 1.5 cm during swallow-induced orad excursion of larynx.

Muscular Components and Their Innervation

A total of 31 paired striated muscles are involved during the preparatory and oral-pharyngeal phases of swallowing. The muscles of the mandible are supplied exclusively by the mandibular branch (V_3) of the trigeminal nerve. The facial-muscle movement, supplied by the facial nerve (VII), plays an important role during chewing. Tongue movement is the major action during chewing and during the oral phase of swallowing, as well as a major component of the pharyngeal phase of swallowing. Tongue movement is determined by the four intrinsic and four extrinsic muscles of the tongue. The intrinsic tongue musculature is innervated by the hypoglossal nerve (XII), and the four extrinsic muscles with the exception of the palatoglossus (X) are innervated by the ansa cervicalis (C_1–C_2), which courses with the hypoglossal nerve. The musculature of the soft palate is under vagal (X) control, except for the tensor veli palatini, which is innervated by V_3. With the exception of the stylopharyngeus, innervated by the glossopharyngeal nerve (IX), all of the pharyngeal muscles (constrictors and levators) including the cricopharyngeus, are innervated by the vagus. Further, the vagus innervates all the intrinsic muscles of the larynx. Seven paired laryngeal muscles are innervated by the vagal recurrent laryngeal nerves, and one pair (the cricothyroids) is innervated by the vagal superior laryngeal nerves. Hyoid and laryngeal movement are produced by suprahyoid and infrahyoid muscle groups innervated by V_3, VII, and the ansa cervicalis (C_1–C_2).

In summary, the muscles of mastication are all innervated by V_3, whereas cranial nerves XII and the ansa cervicalis (C_1–C_2) control the tongue. With few exceptions, the vagus (X) controls the muscles of the palate, pharynx, and larynx. Multiple cranial nerves regulate deglutitive movement of the hyoid and larynx.

Neural Control

The neural control of swallowing involves four major components: (1) efferent motor fibers contained in cranial nerves and the ansa cervicalis; (2) afferent sensory fibers contained in cranial nerves; (3) cerebral, midbrain, and cerebellar fibers that synapse within the midbrain swallowing centers; and (4) paired swallowing centers located in the brainstem. Fibers from the higher CNS centers and oral-pharyngeal sensory fibers send input signals to the brainstem swallowing centers that process the information. Output signals pass via the cranial nerves that operate the muscle machinery of swallowing.

Input Afferent Signals

Sensory cranial nerve input that initiates swallowing goes directly to the swallowing centers, and is provided mainly by

cranial nerves IX and X, with some participation by the maxillary branch (V_2) of the trigeminal and facial (VII) nerves. The facial nerve provides taste fibers over most of the tongue and, of course, touch sensation for the lips and face. The superior laryngeal nerve of the vagus contains sensory fibers for the posterior larynx, base of tongue, and hypopharynx.

Optimal stimuli that elicit swallowing show regional variation [2]. For example, the most effective stimulus is light touch at the fauces, and water in hypopharynx and aditus of the larynx. Taste sensation is a weak stimulus for swallowing. Authorities believe that coded sensory information of a given pattern and intensity from a receptive field of the orad cavity, tongue, and pharynx serves as the major trigger for swallowing. Stimuli, such as the conscious intent to swallow, are thought to facilitate existing input stimuli that are already present as background stimuli. Sensory pharyngeal signals that differ from the code needed to evoke a swallow may elicit a gag, cough, or other patterned responses that use the same muscles as swallowing.

Brainstem Swallowing Centers

Paired swallowing centers reside in the hindbrain. Studies in the dog suggest that only one intact center is needed for normal swallowing [6]. The swallowing centers are not discrete focal areas (Fig. 2), but rather, consist of poorly defined broad areas comprising the nucleus tractus solitarius and

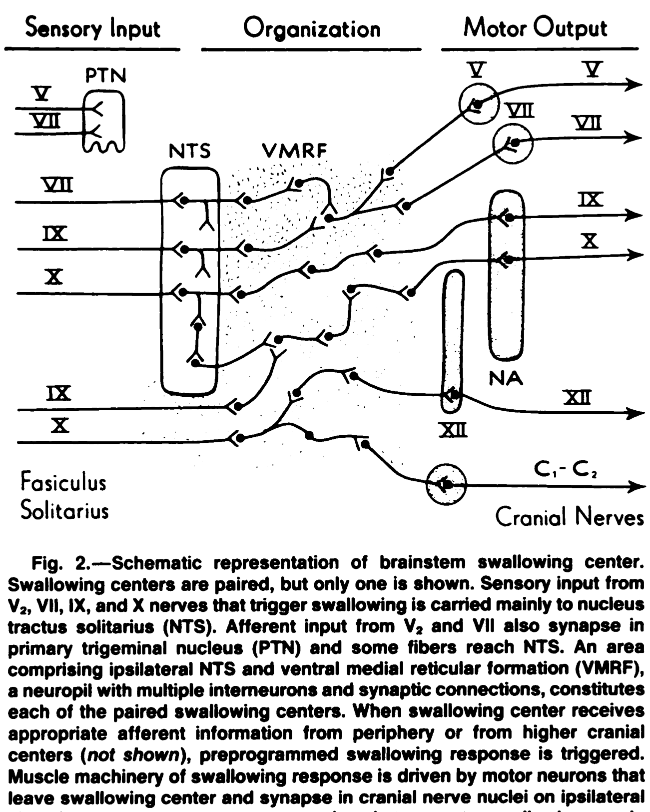


Fig. 2.—Schematic representation of brainstem swallowing center. Swallowing centers are paired, but only one is shown. Sensory input from V_2, VII, IX, and X nerves that trigger swallowing is carried mainly to nucleus tractus solitarius (NTS). Afferent input from V_2 and VII also synapse in primary trigeminal nucleus (PTN) and some fibers reach NTS. An area comprising ipsilateral NTS and ventral medial reticular formation (VMRF), a neuropil with multiple interneurons and synaptic connections, constitutes each of the paired swallowing centers. When swallowing center receives appropriate afferent information from periphery or from higher cranial centers (*not shown*), preprogrammed swallowing response is triggered. Muscle machinery of swallowing response is driven by motor neurons that leave swallowing center and synapse in cranial nerve nuclei on ipsilateral side. Lower motor neurons to muscles that execute swallowing run in cranial nerves V_3, VII, IX, X, and XII as well as in ansa cervicalis (C_1–C_2).

ventromedial reticular formation. Input sensory fibers from the cranial nerves and higher cerebral centers synapse within the nucleus tractus solitarius or reticular formation. Thus, each swallow center consists of an elaborate array of interneurons, or neuropil, that processes incoming information, generates a preprogrammed swallowing response, and distributes the appropriate signals to cranial nerve motor nuclei and their axons, which then deliver neural signals to the many muscles involved in swallowing.

Two major hypotheses have been proposed to describe the neural control mechanism that executes the oral and pharyngeal phases of swallowing: (1) the reflex-chain hypothesis and (2) the central pattern generator hypothesis. According to the reflex-chain hypothesis, a bolus moving through the mouth and pharynx stimulates sensory receptors that sequentially trigger the next step in the swallowing sequence. Even in the absence of a bolus, the posterior excursion of the tongue is thought to stimulate faucial or pharyngeal mechanoreceptors that trigger the pharyngeal swallow. In practical terms the concept of "pharyngeal triggering" is widely used as an operational definition by swallow therapists who treat patients with abnormal swallowing.

The second hypothesis suggests that once swallowing is initiated, it is programmed in a stereotyped manner by the network of nerves in the brainstem swallowing centers, which function independently of any sensory feedback. Currently, evidence exists to support elements of both the reflex-chain and central pattern generator hypotheses. We believe that swallowing occurs as a basic medullary program that may be modified by certain bolus variables, such as volume and consistency [7–10], or in some instances, by voluntary control. For example, swallowed bolus volume alters many of the variables of the swallow sequence, such as the timing and duration of upper esophageal sphincter (UES) opening, but it does not alter other variables such as the magnitude of pharyngeal contraction.

Radiologic Examination

The specific methods used to evaluate the oral and pharyngeal phases of swallowing vary among examiners and whether the examination is being done by a radiologist for a diagnostic evaluation alone, or by a radiologist and speech therapist for diagnosis and assessment of therapy for a "safe swallow" without aspiration. The radiologic examination should include an evaluation of oral and pharyngeal morphology as well as function. Both types of examinations require posteroanterior as well as lateral views [11]. The esophagus should also be elevated. The optimal filming method for oral and pharyngeal morphology is the spot film, whereas imaging for function requires rapid filming, such as videofluorography or cineradiography. We prefer videofluorography to alternative methods because of its lower cost and level of radiation as well as better playback capabilities. In general, optimal examination for morphology is obtained with double-contrast images made with high-density barium (250% wt/vol), and examination for function is done with thin barium (30% wt/vol), thick barium (250% wt/vol), and paste barium. For stud-

ies of function, more than one bolus volume is desirable (e.g., 2–10 ml). Of interest is the fact that the radiologic evaluation of oral-pharyngeal function is an extension of the neurologic function of specific cranial nerves.

The sequencing and filming method requires careful consideration by each examiner. For initial swallows, we prefer a small 2- to 3-ml barium bolus in case the patient exhibits substantial aspiration; a small amount of aspiration does not necessarily terminate the examination and allows additional swallows, to increase the sample size of observation. If the patient tolerates a small 2- to 3-ml bolus, then we proceed to larger bolus sizes, such as 5 and 10 ml and, occasionally, 20 ml. In the search for suspected aspiration, we always use a thin barium preparation and a large barium bolus (e.g., 10 ml) when aspiration is not observed for a 2-ml bolus. When laryngeal penetration or aspiration occurs, we test thick barium, a paste barium bolus, and often different head positions and other therapeutic maneuvers that may prevent aspiration. The examination is terminated if the patient aspirates a substantial amount of barium with each swallow or if the aspirated barium passes below the sternal notch.

After completion of the oral and pharyngeal examinations, the esophagus also should be examined by conventional methods. A limited examination of the esophagus should be attempted even when the delivery of barium to the esophagus is difficult in patients with severe aspiration. A careful search is done for obstructing esophageal lesions (e.g., strictures or rings), abnormal esophageal motor function, and gastroesophageal reflux.

Characteristics of Normal Oral-Pharyngeal Swallowing on the Lateral Projection

A series of images from normal oral-pharyngeal swallowing of a 10-ml bolus of thin barium is shown in Figure 3. The entire swallowing sequence lasts about 1.0–1.5 sec (oral phase about 0.5 sec and pharyngeal phase about 0.7 sec). The oral-pharyngeal swallow is quicker than the eye. Therefore, even rapid filming with 105 images is skimpy because its practical frame rate of 4–6/sec is marginal for adequate coverage of the swallowing sequence. However, imaging at a frame rate of 30/sec by videofluorography or cineradiography is sufficient. These methods allow subsequent slow-motion playback and frame-by-frame analysis.

Bolus Preparation

As part of the bolus preparation, an oral liquid bolus is generally positioned on the dorsum of the tongue, with the tongue tip pressed against the posterior aspect of the maxillary incisors or maxillary alveolar ridge [12]. This initial bolus position leads to the common tipper-type swallow (Fig. 4A). Most of the bolus is located within the midline groove of the tongue (Fig. 5A) and in a spoonlike depression of the mid tongue (Fig. 4A). The posterior part of the tongue elevates against the soft palate, which pushes downward to keep the bolus from escaping from the mouth with premature bolus entry into the pharynx. Thus, closure of the posterior tongue against the soft palate [13, 14] functions as a glossopalatal sphincter.

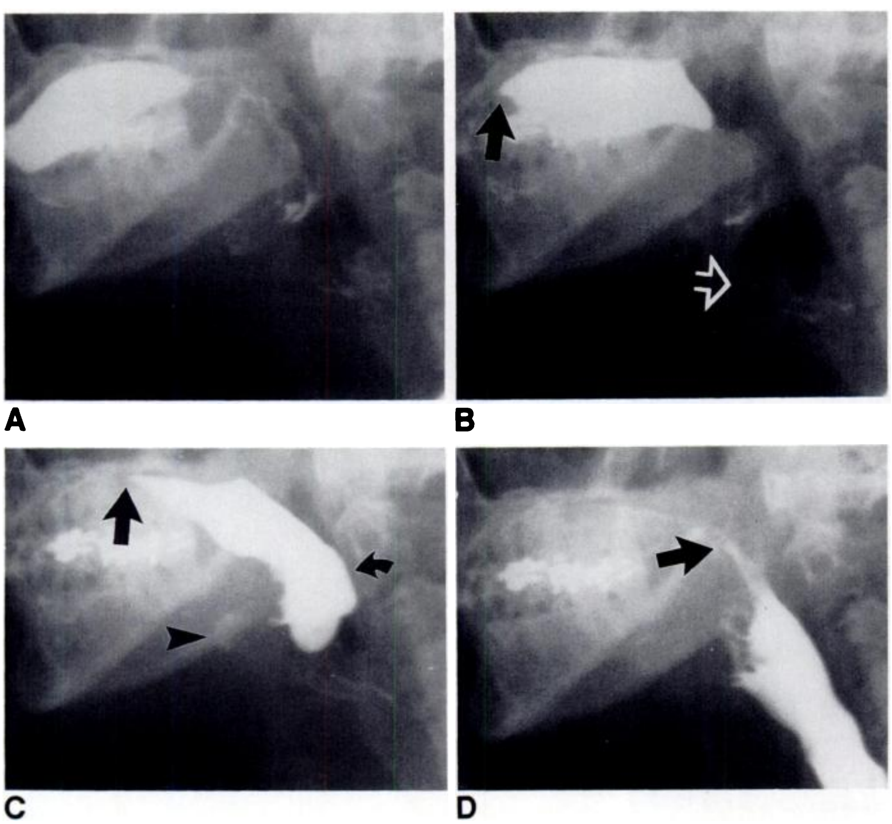


Fig. 3.—Overview of oral and pharyngeal swallowing sequence in a normal subject. Four images taken 0.03 sec apart during swallowing sequence of 10-ml barium bolus.

***A*, Bolus is positioned in supralingual position with tongue tip against maxillary incisors. Posterior oral cavity is sealed off from oropharynx by approximation of posterior tongue and soft palate.**

***B*, With initiation of swallowing, superior surface of tongue makes sequential contact (*solid arrow*) with hard palate in peristaltic sequence that begins to propel bolus into oropharynx. Bolus head is just reaching fauces. Air is seen in open laryngeal vestibule (*open arrow*).**

***C*, Small amount of air still remains in laryngeal vestibule. As glossopalatal sphincter opens, tongue base moves forward and palate moves upward and backward to make contact with posterior pharyngeal wall (*curved arrow*), thereby sealing off nasopharynx. Hyoid (*arrowhead*) is well into its orad excursion and now overlaps posterior mandible. Little air is seen in laryngeal vestibule. Head of bolus fills valleculae. Tail of bolus (*straight arrow*).**

***D*, Mouth is now empty of barium, and peristaltic stripping wave is seen at bolus tail (*arrow*) in oropharynx. Hyoid has moved further orad, and closed vestibule is now devoid of air. Valleculae are empty. Upper esophageal sphincter is fully open, and barium flows freely across sphincter into cervical esophagus.**

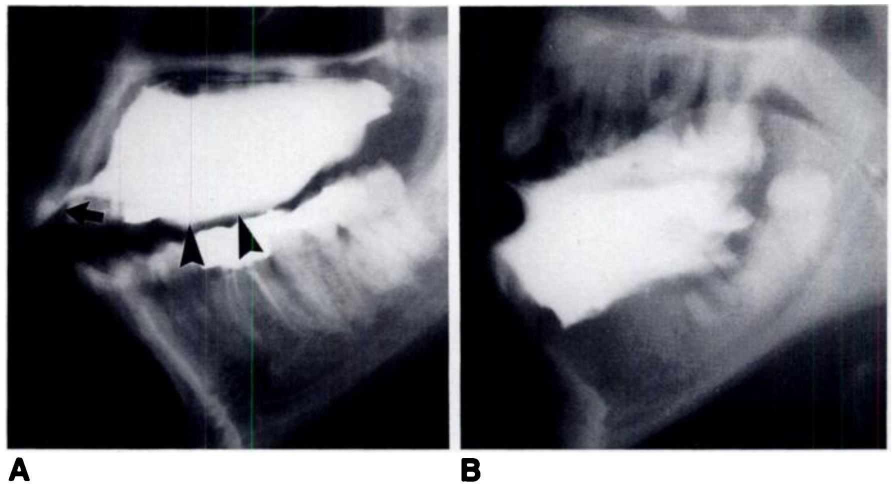


Fig. 4.—Initial bolus and tongue position for two major types of normal oral swallow. Both examples are with 10-ml bolus of barium.

***A*, Tipper swallow. Tip of tongue (*arrow*) is positioned immediately behind and in contact with maxillary incisors and maxillary alveolar ridge. Bolus is stored in spoonlike depression (*arrowheads*) on dorsum of tongue. With onset of swallowing, tongue tip sweeps posteriorly with powerful peristaltic motion to deliver bolus into oropharynx.**

***B*, Dipper swallow. At onset of swallowing, major part of bolus is beneath tongue tip in anterior sublingual meatus (tongue tip obscured by barium). With onset of swallowing, tongue tip must dip beneath bolus in a scooping motion to elevate bolus to a supralingual position. Then tongue motion proceeds as in tipper-type swallow.**

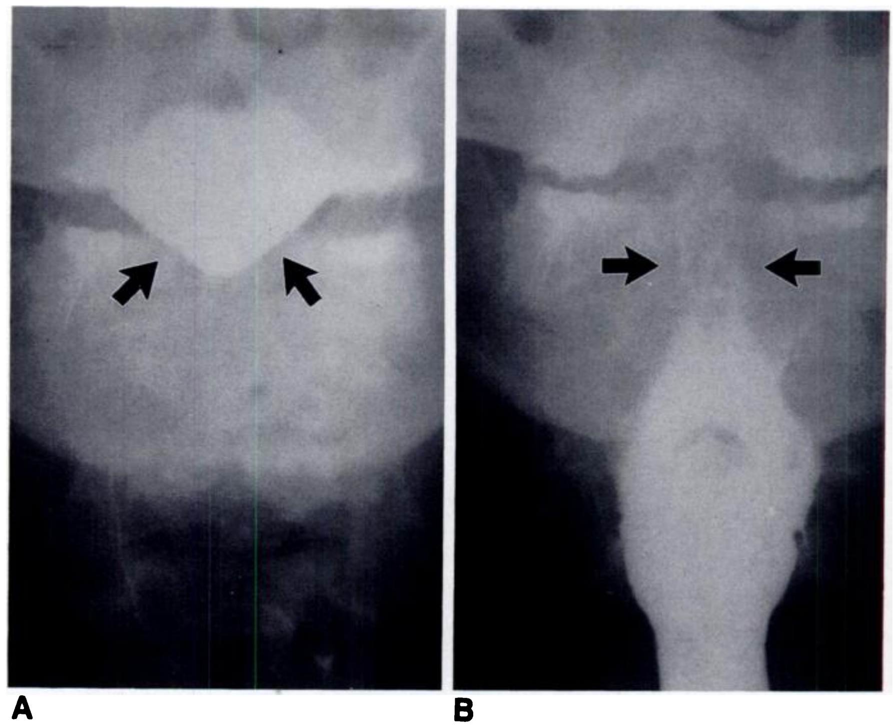


Fig. 5.—Posteroanterior projections of barium swallow in normal subject.

***A*, Just before swallowing begins, barium is seen nestled in deep midline groove (*arrows*) on posterior half of tongue.**

***B*, During early pharyngeal phase of swallowing, barium has entered oropharynx. Superior constrictors approximate one another (*arrows*) in coronal plane.**

Oral Phase of Swallowing

As a variant of normal, some subjects exhibit a dipper-type swallow wherein the bolus is initially located beneath the anterior tongue, within the anterior sublingual sulcus (Fig. 4B). With the bolus in this position, the tongue at the onset of swallowing must dive beneath the bolus to scoop it to a supralingual position. With this motion, the tongue tip reaches the posterior aspect of the maxillary incisors and the dipper- and tipper-type swallows then proceed in the same manner [12]. The anterior two-thirds of the tongue elevates as a globular mass to make sequential peristaltic contact with the hard palate to impart a V-shaped configuration [15, 16] to the bolus tail (Fig. 6B).

The tongue rolls posteriorly in pistonlike motion to thrust the bolus into the oropharynx. Concurrently, the base of the tongue moves downward and forward to expand the hypopharynx and provide a chute down which the bolus flows into the pharynx (Fig. 6C). Simultaneously, the palate moves upward to open the zone of the glossopalatal sphincter, thereby further facilitating flow between the oral and pharyngeal cavities (Fig. 6C). Concurrently, the palate contacts the posterior pharyngeal wall to seal off the nasopharynx from the oropharynx and thereby prevent nasal regurgitation. This sealing movement of the palate is more than simply an upward swing of a trap door. Rather, the side walls of the nasopharynx, comprising the superior pharyngeal constrictors, also oppose one another (Fig. 5B) to make a forceful circular closure.

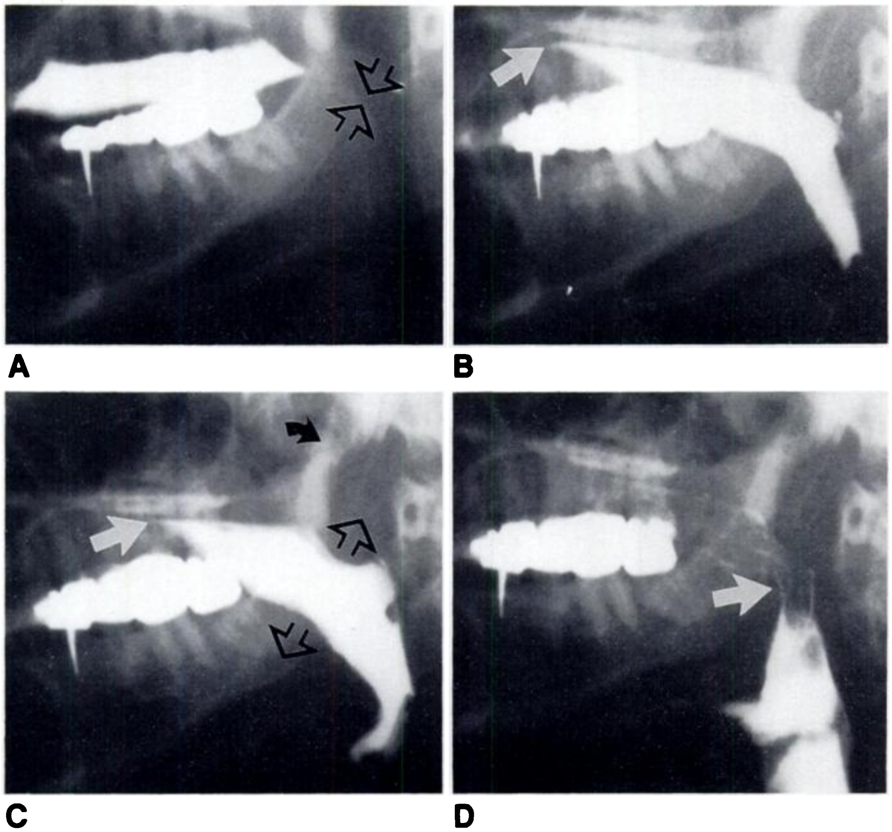


Fig. 6.—Opening of glossopalatal sphincter during 10-ml barium swallow in normal subject. *Straight solid arrows* indicate tail of barium bolus, which is propelled by peristaltic sequence of tongue against palate or against pharyngeal constrictors.

***A*, Bolus positioned in mouth. Glossopalatal sphincter (*open arrows*) is closed and thereby prevents barium from spilling prematurely into pharynx.**

***B*, Oral swallow initiated. Glossopalatal sphincter has opened and barium begins to enter oropharynx.**

***C*, Glossopalatal sphincter now fully open (*between open arrows*) and barium flows down chute into pharynx. Tongue base (*lower open arrow*) has moved forward to expand pharynx. Soft palate (*upper open arrow*) has moved posteriorly to open oral-pharyngeal junction and also seal off nasopharynx. Prominent posterior bulge or buckle (*curved arrow*) of soft palate is caused by contraction of levator veli palatini.**

***D*, Tail of bolus (*arrow*) is in oropharynx, and glossopalatal sphincter has closed as tongue base moves backward to contact posterior pharyngeal wall.**

In addition to elevation of the soft palate, several other events occur that make room for the swallowed bolus to enter the oropharynx. The posterior tongue (Fig. 6), hyoid, and larynx move upward and forward to expand the pharynx in the sagittal plane. In effect, the bolus slides down the ramp, or chute, created by the flattening and forward movement of the posterior tongue (Figs. 6B and 6C). Additionally, shortening of the pharyngeal levators (e.g., stylopharyngeus) serves to expand the transverse diameter of the pharynx (Fig. 7B).

Pharyngeal Phase of Swallowing

As the bolus enters the oropharynx, the posterior tongue makes a rapid posterior pistonlike motion to drive the bolus through the oropharynx into the hypopharynx (Fig. 6D). The posterior chamber for the posterior lingual piston is formed by the posterior pharyngeal wall, which stiffens because of the sequential contraction of its three constrictors (superior, middle, and inferior). Thus, bolus pulsion through the pharynx is a combination of posterior tongue thrust and sequential caudally oriented contraction of the pharyngeal constrictors [17]. Similar to its appearance in the oral cavity (Fig. 6), the bolus tail in the pharynx has a V-shaped configuration [15, 18]. Because the bolus head moves faster than the bolus tail, the bolus elongates in the pharynx, acts as a force that contributes to UES opening, and rapidly enters the proximal esophagus. Normal UES opening occurs in a generous unrestricted fashion (Fig. 3D). The diameter of sphincter opening depends directly on the volume of the swallowed barium bolus [19].

Normally, the oral phase and pharyngeal phases of swallowing are coupled so tightly together that the first oral phase blends in smoothly with the second pharyngeal phase. Some believe that the oral phase of swallowing triggers the pharyngeal phase when the posterior tongue compresses the tonsillar pillars or delivers a bolus into the oropharynx. An alternative possibility is that the relationship between the oral and pharyngeal phases of swallowing is mainly programmed by the brainstem swallowing center.

The normal pharyngeal phase of swallowing involves (1) palatal closure, (2) bolus transport through the pharynx, (3) glottal closure to prevent aspiration, and (4) UES opening and transsphincteric fluid flow. We propose that normal UES opening involves four elements: (1) transient relaxation, about 0.5 sec, of a tonically contracted UES; (2) low compliance, or easy stretchability, of the relaxed UES; (3) forward traction on the relaxed compliant UES by anterior movement of the hyoid, which acts on the larynx; and (4) radial pressure forces within an oncoming bolus that fully distend the relaxed UES, once it is opened initially by hyoid traction [19]. Manometric studies demonstrate that the resting UES exhibits a high-pressure zone that is higher posteriorly and anteriorly than laterally because of the cricopharyngeal configuration [20]. Pullthroughs of pressure sensors across the UES indicate that the cricopharyngeus is the major muscle element of the UES [19, 21]. During swallowing the UES high-pressure zone

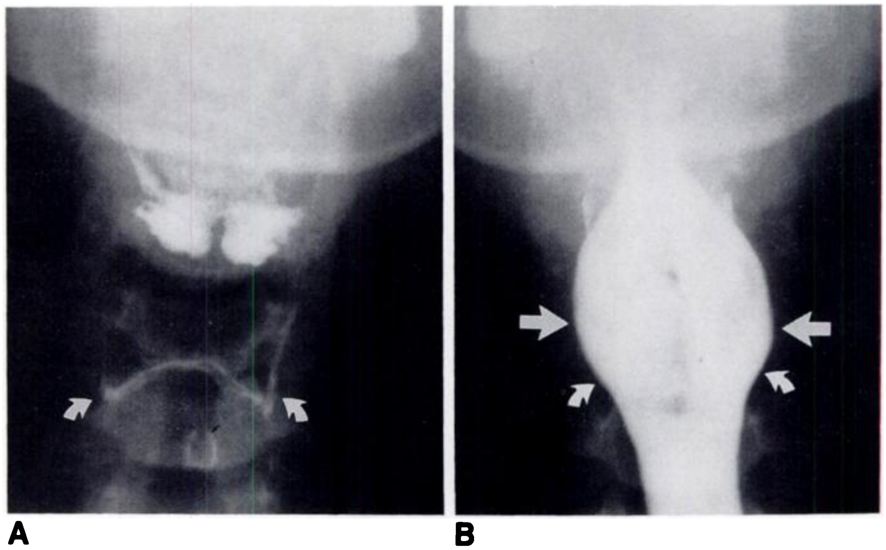


Fig. 7.—Posteroanterior view. Effacement of piriform sinuses during barium swallow in normal subject.

***A*, Before swallowing begins, piriform sinuses (*arrows*) are seen outlined with barium.**

***B*, During pharyngeal phase of swallowing, piriform sinuses (*curved arrows*) have moved upward and are effaced. Coronal diameter of pharyngeal side walls (*straight arrows*) has increased. Upper esophageal sphincter is at junction of funnel-shaped pharynx and straight tube of cervical esophagus.**

as well as its underlying electromyographic activity relax. In fresh anatomic specimens, the atonic compliant cricopharyngeus is readily stretched by gentle traction.

At the onset of swallowing, the hyoid, because of contraction of the suprahyoid muscles, begins an orad excursion that has superior and anterior components (Fig. 8). The larynx moves with the hyoid because of interconnections (Fig. 1) of the thyrohyoid membrane, and paired thyrohyoid muscles. Therefore, the larynx moves forward along with the anterior movement of the hyoid. Thus, the hyoid exerts traction on the larynx, which imparts anterior traction on the cricoid, which in turn exerts forward traction on the UES. This anterior traction force causes an initial opening (about 6 mm) of the relaxed UES [19].

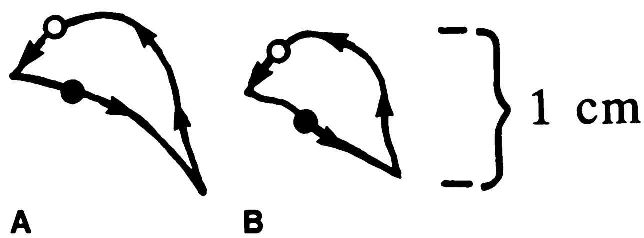


Fig. 8.—*A* and *B*, Oral excursion loops made by hyoid in normal subject during swallowing 10-ml (*A*) and 1-ml (*B*) boluses of barium. *Arrows* indicate direction of movement. *Open circles* indicate upper esophageal sphincter opening; *solid circles* indicate closure. Note that hyoid makes a greater superior and anterior excursion for 10-ml bolus than for 1-ml bolus.

Once the UES is open, the swallowed barium bolus begins to enter the sphincter segment. When the sphincter segment is penetrated by the barium bolus, pressure forces within the bolus serve to further expand the UES segment. In some instances, a faint transient bulge of the cricopharyngeus is seen during the swallowing sequence. This slight indentation of the cricopharyngeus is normally transient and rapidly disappears (Fig. 9). Generally, however, the UES segment opens fully without a trace of a cricopharyngeal indentation. The duration of UES opening and UES diameter depend directly on bolus volume and viscosity [10, 19]. Superior hyoid movement lasts about 1.2 sec, straddles the oral and pharyngeal phases of swallowing, and persists from the onset of the swallow until the end of the swallow. UES opening and closing occur while the hyoid and larynx are near or at the apogee of their oral excursion (Fig. 8).

During the pharyngeal phase of swallowing, the laryngeal vestibule closes for about 0.6–0.7 sec, beginning just before UES opening (Fig. 10). Closure of the vestibule depends largely on movement of the epiglottis, which is governed mainly by contraction of the thyrohyoid muscles (Figs. 11 and 12). Deglutitive epiglottal movement occurs as a two-step process [22]. First, the epiglottis moves from an upright to a horizontal position, caused mainly by elevation of the hyoid and larynx as well as by contraction of the paired thyrohyoid muscles. The flip of the free margin, or tongue, of the epiglottis is accomplished mainly by the aryepiglottic and thyroepiglottic muscles once the epiglottis is horizontal, by using the approximated arytenoids as a fulcrum. Contraction of these muscles also acts as a sphincter at the laryngeal introitus. The elastic epiglottis rapidly flips downward. In some cases, however, an elongated epiglottis is mechanically blocked from flipping downward by the posterior pharyngeal cervical wall, cervical spine, or indwelling nasogastric tube. The beginning of vestibular closure corresponds to horizontal movement of the epiglottis, which acts in a bellowslike movement to empty gas rapidly from the vestibule. Thus, initial vestibular closure ejects a puff of gas into the pharynx; this tends to help prevent swallowed material from entering the airway. Vestibular closure alone, however, does not guarantee a lack of barium penetration. In some normal subjects slight barium penetration of the vestibule is seen on one or two barium swallows, particularly the initial swallow (Fig. 9). Such penetrations are generally cleared rapidly during the swallow.

To this point, we have discussed the evaluation of the normal oral and pharyngeal swallow nearly entirely in qualitative terms. During the past several years, however, considerable effort has developed to quantify swallowing [7, 18, 23,

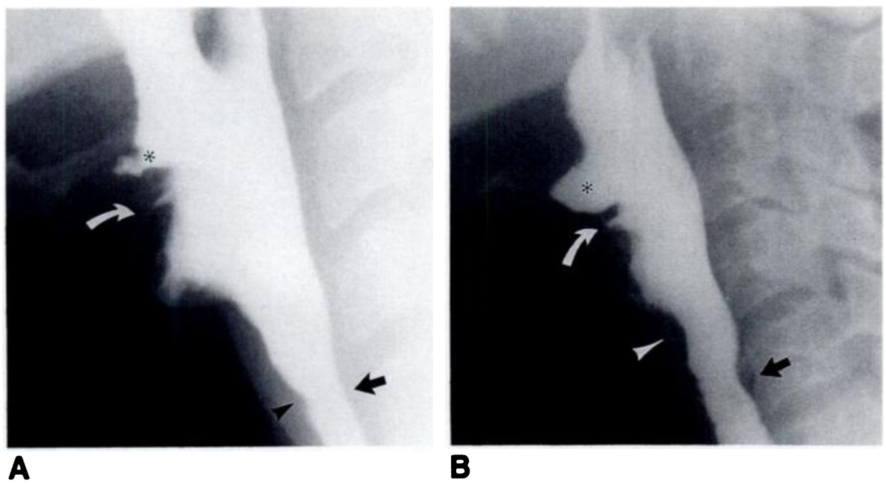


Fig. 9.—Examples of mild posterior bulge (*straight arrows*) of cricopharyngeus during pharyngeal phase of 10-ml barium swallow in two young healthy volunteers. Also seen in both examples is a postcricoid impression (*arrowheads*) and mild penetration (*curved arrows*) of laryngeal vestibule. Valleculae (*asterisks*).

***A*, 22-year-old man. Mild cricopharyngeal impression disappeared later during pharyngeal swallow of laryngeal vestibule.**

***B*, 25-year-old man. Mild cricopharyngeal impression was not seen during 15-ml barium swallow. Ventricular penetration of barium was eliminated later during pharyngeal swallow.**

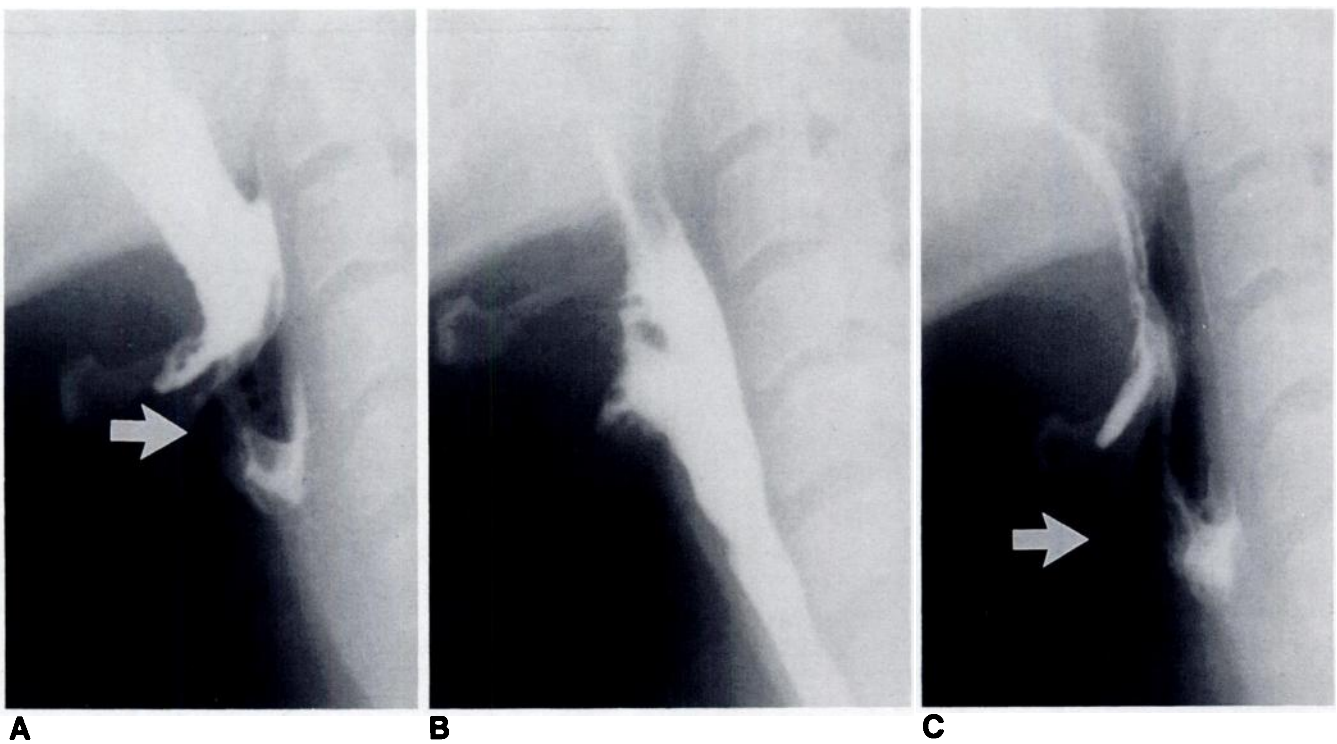


Fig. 10.—Closure and opening of laryngeal vestibule during 10-ml barium swallow in a normal subject.

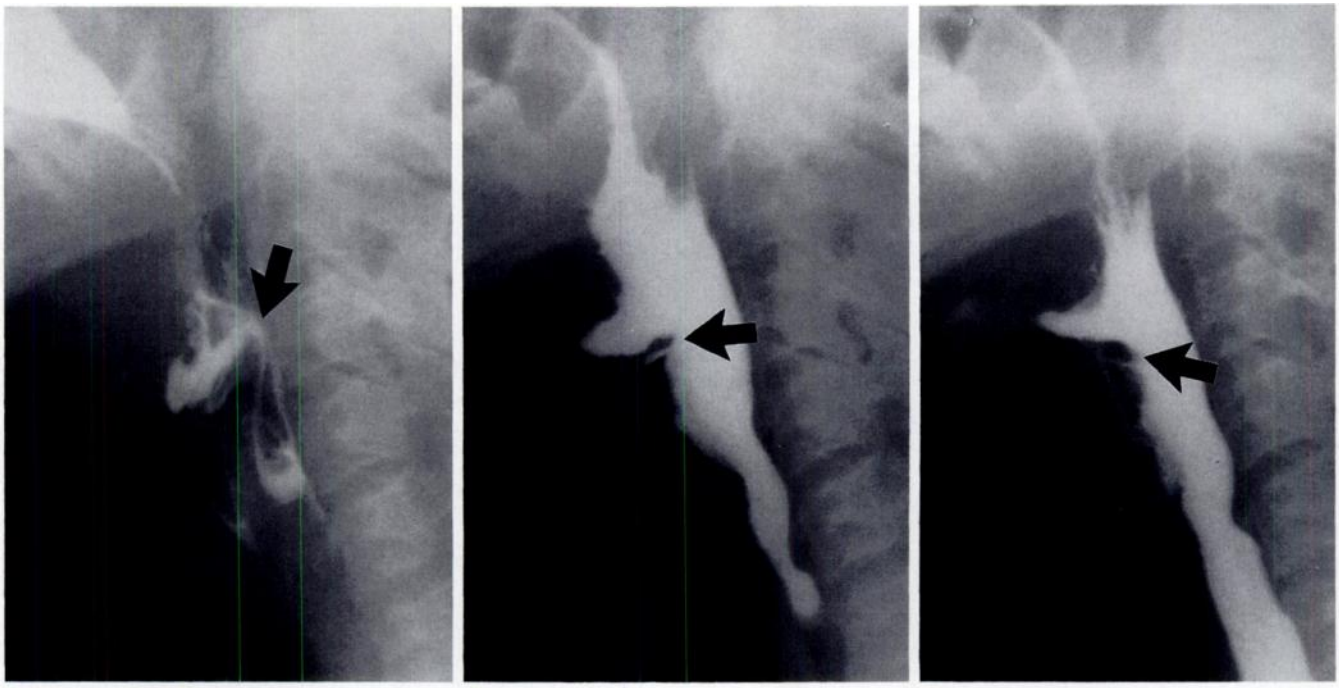
***A*, Head of bolus has just reached valleculae and free margin of epiglottis is upright. Air is seen in open laryngeal vestibule (*arrow*).**

***B*, Laryngeal vestibule is now closed and devoid of air. Barium flows freely across open upper esophageal sphincter.**

***C*, Pharyngeal swallowing now complete. Laryngeal vestibule has reopened and is refilled with air (*arrow*).**

24]. Such efforts involve assessment of the relative timing of events in the swallowing sequence, for example, timing of events (e.g., vestibular closure), calculation of durations (e.g., UES opening), and measurement of distances (e.g., hyoid movement). Initially, these measurements were done entirely by hand, but recently have been aided by computer methods [24].

The two primary functions of pharyngeal swallowing are to transport a swallowed bolus through the pharynx while protecting the airway from aspiration. A number of mechanisms converge to achieve airway protection. Many mechanisms that contribute to airway protection also contribute to bolus transport. For example, during hyoid elevation and thyrohyoid shortening, the glottis becomes locked to the hyoid as a single unit so that the angle of the laryngeal introitus tilts forward and downward so that it is protected by the overhanging epiglottis. Additionally, elevation of the larynx and UES shorten the distance that a bolus must travel and, therefore, the interval for potential aspiration. Opening of the UES by a liquid bolus requires only a low intrabolus pressure



A B C

Fig. 11.—Epiglottal movement during swallowing of 10-ml barium bolus in normal subject. Images separated by 0.03-sec intervals.
A, Bolus head is just leaving mouth. Epiglottis (*arrow*) is obliquely upright.
B, Bolus head has just entered region of upper esophageal sphincter. Epiglottis (*arrow*) is now horizontal.
C, Upper esophageal sphincter is now fully open, although there is a slight impression from cricopharyngeus. Barium flows freely into cervical esophagus. Free margin, or tongue, of epiglottis (*arrow*) has flipped caudally. Laryngeal vestibule (not well seen) is closed.

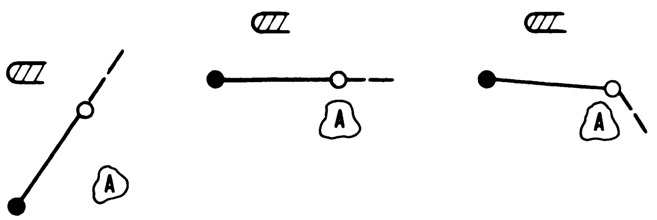


Fig. 12.—Schematic representation of normal epiglottal movement during swallowing. Hyoid is marked by hatching. A = Arytenoid cartilage. Body of epiglottis is attached to hyoid cartilage at *solid circles*, and *open circles* indicate junction of body and tongue of epiglottis. During resting conditions (*left*) epiglottis exhibits a vertical oblique position. During swallowing, hyoid (middle) epiglottis and larynx all move superiorly. Epiglottis acquires a horizontal orientation. During middle phase of pharyngeal swallow (right), arytenoid cartilages have approximated one another to close vocal cords (*not shown*) and moved forward to contact the body of epiglottis. In this position, arytenoids (A) act as a fulcrum to give a mechanical advantage over which free margin of epiglottis bends to flip caudad. This flip is executed mainly by contraction of aryepiglottic and lateral thyroepiglottic muscles.

Fig. 13.—Posteroanterior image of 5-ml barium swallow in asymptomatic subject. Smooth right-sided pharyngeal pouch (*arrow*) appeared early during pharyngeal phase of swallowing (i.e., 0.5 sec after onset of swallowing) and disappeared by middle part of pharyngeal phase (i.e., by 0.8 sec). Barium is seen to split at horizontal free margin of epiglottis (horizontal filling defect in the barium column) and flow mainly down lateral side channels of pharynx.

in the pharynx so that only a low-pressure gradient exists between the bolus and larynx [19]. Intrinsic muscles of the glottis forcefully approximate the true vocal cords. Effacement of the piriform sinuses creates lateral food channels so that the bolus generally deviates laterally around the epiglottis (Fig. 13), thereby making minimal contact with the closed vestibule. Any residual fluid trapped in the piriform sinus after the swallow is normally at a lower level than the laryngeal vestibule, thereby retarding aspiration after the swallow.

Overall, the larynx closes from below upward: first, the vocal cords, then the false cords (in some cases), then the lower vestibule (approximation and forward movement of the arytenoids), and then the upper vestibule (horizontal position of

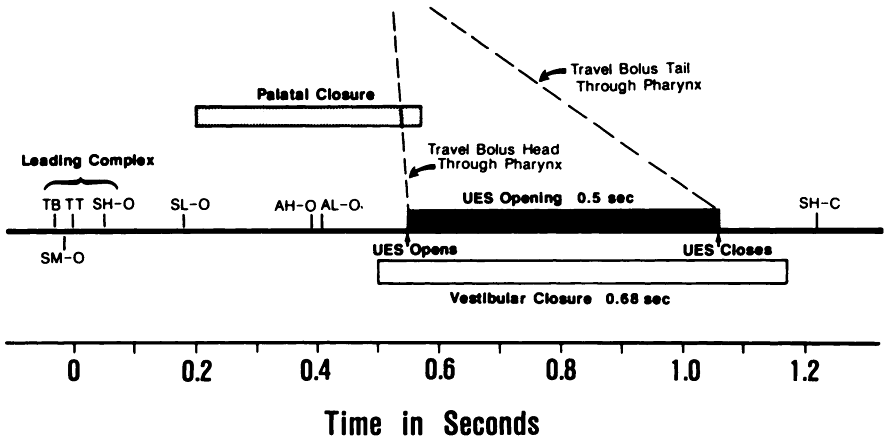


Fig. 14.—Time line of 5-ml barium bolus swallow in normal subject. Reference time of zero is used as onset of propulsive tongue tip (TT) movement at maxillary incisors. This movement begins to propel bolus toward pharynx. Other notations include tongue base movement (TB), onset of superior hyoid movement (SH-O), onset of submental electric activity (SM-O), onset of superior laryngeal movement (SL-O), onset of anterior hyoid movement (AH-O), onset of anterior laryngeal movement (AL-O), and completion of superior hyoid movement (SH-C). Palatal closure occurs as barium bolus flows from mouth into oropharynx. *Broken lines* indicate flow of bolus head and tail, respectively, through pharynx. Upper esophageal sphincter (UES) opening occurs when bolus head reaches UES; UES closes when bolus tail reaches sphincter. In this example, closure of laryngeal vestibule straddles the interval that the bolus is in the pharynx. Entire swallowing sequence lasted about 1.2 sec.

the epiglottis contacts closed arytenoids). Opening of the larynx proceeds from above downward.

One useful method for quantifying swallow-related events is the time line (Fig. 14). The initial events in swallowing include onset of superior hyoid movement, onset of submental electromyographic activity [18], and vocal cord closure. These events form the leading complex of swallowing. In most swallows, vocal cord closure is the first event and vocal cord opening the last event. Events in the leading complex generally occur within 0.1–2.0 sec of one another. Next, the onset of palatal closure occurs at about 0.35 sec before UES opening. The onset of anterior hyoid movement occurs about 0.15 sec before UES opening. UES opening with transsphincteric flow for a 5-ml barium bolus last about 0.5 sec. UES closure occurs as the pharyngeal peristaltic wave reaches the UES. Oral transit time (tail of bolus at maxillary incisors until it reaches the fauces) measured by videofluoroscopy is the equivalent of that measured by manometry because passage of the barium tail by a manometric sensor corresponds to the upstroke onset of the manometric pressure complex [16]. Because of the way it is measured, oral transit, about 0.5 sec, equals oral clearance time [18]. Pharyngeal transit, about 0.7 sec, is measured in the same manner as oral transit. However, pharyngeal transit (entry bolus head into pharynx until tail reaches UES) is faster than pharyngeal clearance because the bolus head enters the pharynx before the bolus tail. These distinctions need to be recognized when making such measurements and comparing measurements between studies.

Appearance of Normal Swallow on Frontal Projection

For assessment of the first two phases of swallowing, the mouth and pharynx should be viewed in the frontal as well as in the lateral projection. With the bolus positioned in the mouth awaiting swallowing, the midline tongue groove is often evident (Fig. 5A). Some of the bolus may be positioned within the buccal pouches, which are cleared during the oral phase of swallowing, or, in some instances, part of the oral bolus may escape into the buccal pouches during oral swallowing. In some subjects, midline apposition of the superior pharyngeal walls at the nasopharynx is seen during swallowing (Fig. 5B). The valleculae generally disappear during swallowing as the epiglottis moves to a horizontal position and its free margin flips downward. The valleculae normally evert and evacuate (Figs. 3 and 6). Small amounts of residual barium within normal-sized valleculae are a normal variant. As the free margin of the epiglottis becomes horizontal, its free margin is often seen as a transverse defect within the horizontal column (Fig. 13). Later, in the pharyngeal phase, the epiglottis projects an inverted V, or chevron configuration, within the barium column. During pharyngeal swallowing, the piriform sinuses make a brisk upward movement, largely governed by the four levator muscles of the pharynx. During their superior excursion, the piriform sinuses normally invert and evacuate their contents into the pharynx (Fig. 7B). Inversion of the piriform sinuses is caused by contraction of the levator muscles of the pharynx. At the onset of swallowing, the vocal cords begin to close and move upward with the larynx. The posteroanterior view is also useful for evaluating the vocal cord approximation during phonation (e.g., "ee") and for examining for unilateral cord paralysis. In many subjects, barium flows around the closed glottis as two lateral channels (Fig. 13) that meet 1–2 cm above the UES (Fig. 7B). The pharynx projects as a funnel. The level of the UES is readily identified as the junction of the pharyngeal funnel and the cervical esophagus, where slight wasting may be transiently present. At the completion of the posteroanterior examination for pharyngeal motor function, the pharyngeal walls are generally well coated with barium, and several spot films may be obtained for an evaluation of pharyngeal morphology. A Valsalva maneuver with an open glottis or having the patient pronounce the sound "ooo" will expand the piriform sinuses for better imaging. Slightly oblique images (15–20°) are often helpful for better imaging of the piriform sinuses and aryepiglottic folds.

From the preceding description, it is clear that an oral-pharyngeal swallow comprises a number of component elements that are synchronized in a fluid sequence. Each element needs to be evaluated in the assessment of swallowing function. When rapid-filming recording methods with slow-motion playback capability are available, each component can be evaluated fluoroscopically during the same swallowing sequence. Otherwise, each component needs to be evaluated during separate swallows because the swallowing sequence

is too complex to focus on all of the components during a single swallow.

Normal Morphologic Variants

Morphologic variants that may be observed in normal asymptomatic subjects include a postcricoid impression, pharyngeal outpouches (Fig. 13), small cervical web, and slight posterior impression of the cricopharyngeus during swallowing. Several decades ago the postcricoid impression (Fig. 9) was commonly diagnosed as a neoplasm until it became recognized that this impression was a frequent finding during the pharyngeal phase of swallowing. Initially, the impression was attributed to a postcricoid plexus of veins [25]. In our opinion, however, the postcricoid impression is simply a mucosal plication because large-sized veins are not located behind the cricoid lamina. Thin mucosal webs about 1–2 mm in height, usually located on the anterior wall of the cervical esophagus, are a common incidental finding of no clinical significance [26, 27]. More pronounced and extensive webs that are hemispheric or circumferential may cause sufficient luminal narrowing to result in dysphagia for solids. Most pharyngeal outpouches are a transient incidental finding in asymptomatic subjects. Such pharyngeal pouches generally appear and disappear early during the pharyngeal phase of swallowing [28]. Another morphologic aberration seen commonly in asymptomatic individuals is a slight impression by the cricopharyngeus that may occur early, late, or during the interval of UES opening and transsphincteric flow of barium (Fig. 9). Such mild impressions may be effaced by a large bolus of barium (e.g., 15 or 20 ml). Some believe that any impression by the cricopharyngeus is abnormal [29, 30]. Our bias is that a mild cricopharyngeal impression is within the range of normal and does not cause clinical symptoms. Further investigation is needed, however, to resolve this issue.

Swallowing in Infants and Children

Although a full discussion of swallowing in children and infants is beyond the scope of the present discussion, some mention of infantile-type swallowing is warranted. In infants, the tongue is oversized and fills the mouth; the hyoid has a high position at the level of the mandible. During nursing, the mouth is filled by an oral suckle consisting of compression of the nipple and oral suction. Fluid from each suckle is pumped back into the pharynx, which when full, triggers a pharyngeal swallow. Normally, two or three suckles precede every pharyngeal swallow. During the pharyngeal swallow, the hyoid moves only forward because it is already located in a high superior position. Because of the high resting position of the hyoid, epiglottis, and larynx, infants are alleged to suckle and swallow while they breathe through their nose. During maturation, the hyoid descends and the pharynx becomes larger and the tongue relatively smaller because of differential growth of the mandible and tongue. These developments are accompanied by the ability to chew and manipulate food in the mouth. These developmental changes enable delivery of larger boluses into the pharynx and resonatation of speech in the pharynx. Interestingly, the adult pattern of swallowing recapitulates that of the infant in that the hyoid and larynx transiently assume a high superior position during swallows.

REFERENCES

1. Logemann JA. *Manual for the videofluorographic study of swallowing*. San Diego: College-Hill Press, **1986**
2. Miller AJ. Deglutition. *Physiol Rev* **1982**;62:129–184
3. Dodds WJ. The physiology of swallowing. *Dysphagia* **1989**;3:171–178
4. Dent J, Dodds WJ, Friedman RH, Sekiguichi T, Hogan WJ, Arndorfer RC. Mechanisms of lower gastroesophageal reflux in recumbent asymptomatic human subjects. *J Clin Invest* **1980**;65:256–267
5. Lichter I, Muir RC. The pattern of swallowing during sleep. *Electroencephalogr Clin Neurophysiol* **1975**;38:427–432
6. Doty RW, Bosma JF. An electromyographic analysis of reflex deglutition. *J Neurophysiol* **1956**;19:44–60
7. Dodds WJ, Man KM, Cook IJ, Kahrilas PJ, Stewart ET, Kern MK. Influence of bolus volume on swallow-induced hyoid movement in normal subjects. *AJR* **1988**;150:1307–1309
8. Kahrilas PJ, Dodds WJ, Dent J, Logemann JS, Shaker R. Upper esophageal sphincter function during deglutition. *Gastroenterology* **1988**;95:52–62
9. Dantas RO, Dodds WJ, Massey BT, Kern MK. The effect of high- vs low-density barium preparations on the quantitative features of swallowing. *AJR* **1989**;153:1191–1195
10. Dantas RO, Kern MK, Massey BT, et al. Effect of swallowed bolus variables on the oral and pharyngeal phases of swallowing. *Am J Physiol* (in press)
11. Jones B, Donner MW. Examination of the patient with dysphagia. *Radiology* **1988**;167:319–326
12. Dodds WJ, Taylor AJ, Stewart ET, Kern MK, Logemann JA, Cook IJ. Tipper and dipper types of oral swallows. *AJR* **1989**;153:1197–1199
13. Rubesin SE, Jones B, Donner MW. Radiology of the adult soft palate. *Dysphagia* **1987**;2:8–17
14. Dantas RO, Dodds WJ, Massey BT, Shaker R, Cook IJ. Manometric characteristics of the glossopalatal sphincter. *Dig Dis Sci* (in press)
15. Sokol EM, Heitmann P, Wolf BS, Cohen BR. Simultaneous cineradiographic and manometric study of the pharynx, hypopharynx and cervical esophagus. *Gastroenterology* **1966**;51:960–974
16. Shaker R, Cook IJS, Dodds WJ, Hogan WJ. Pressure-flow dynamics of the oral phase of swallowing. *Dysphagia* **1988**;3:79–84
17. Ramsey GH, Watson JS, Gramiak R, Weinberg SA. Cinefluorographic analysis of the mechanism of swallowing. *Radiology* **1955**;64:498–518
18. Cook IJ, Dodds WJ, Dantas RO, et al. Timing of videofluoroscopic, manometric events and bolus transit during the oral and pharyngeal phases of swallowing. *Dysphagia* **1989**;4:8–15
19. Cook IJ, Dodds WJ, Dantas RO, et al. Opening mechanisms of the human upper esophageal sphincter. *Am J Physiol* **1989**;20:G748–G759
20. Dodds WJ, Kahrilas PJ, Dent J, Hogan WJ. Considerations about pharyngeal manometry. *Dysphagia* **1987**;1:209–214
21. Asoh R, Goyal RD. Manometry and electromyography of the upper esophageal sphincter in opossum. *Gastroenterology* **1978**;74:514–520
22. Curtis DJ, Sepulveda GU. Epiglottic motion: video record of muscular dysfunction. *Radiology* **1983**;148:473–477
23. Curtis DJ, Cruess DF, Dachman AH, Maso E. Timing in the normal pharyngeal swallow. *Invest Radiol* **1984**;19:523–529
24. Logemann JA, Kahrilas PJ, Begelman J, Dodds WJ, Pauloski BR. Interactive computer program for biomechanical analysis of videoradiographic studies of swallowing. *AJR* **1989**;153:277–280
25. Pitman RG, Fraser GM. The post-cricoid impression on the oesophagus. *Clin Radiol* **1965**;16:34–39
26. Clements JL Jr, Cox GW, Torres WE, Weens HS. Cervical esophageal webs—a roentgen-anatomic correlation. Observations on the pharyngoesophagus. *AJR* **1974**;121:221–231
27. Nosher JL, Campbell WL, Seaman WB. The clinical significance of cervical esophageal and hypopharyngeal webs. *Radiology* **1975**;117:45–47
28. Curtis DJ, Cruess DF, Crain M, Sivit C, Winters C Jr, Dachman AH. Lateral pharyngeal outpouchings: a comparison of dysphagic and asymptomatic patients. *Dysphagia* **1988**;2:156–161
29. Asherson N. Achalasia of the cricopharyngeal sphincter. *J Laryngol Otol* **1950**;64:747–758
30. Sutherland HD. Cricopharyngeal achalasia. *J Thorac Surg* **1962**;43: 114–126